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Construction Equipment for Lunar Surface Operations

by
James W. Brazell
Alvin Smith

Future endeavors in space will be shaped by the concept of extraterrestrial surface bases. The lunar environment presents an extraordinary challenge in designing equipment and machinery to operate during lunar exploration missions and to construct a lunar base or early outpost. Because familiar terrestrial machines are so large, it is prohibitively expensive to move them to the moon. Also, they could not accomplish all the required work tasks. The objective of this study was to create conceptual models of equipment and machines suitable for operation on the surface of the moon.

This report presents the design concepts for five machine variations and eight implements for mobility, lifting, digging, etc. The implements may be regarded as somewhat universal since they may be used with most of the machine concepts described. It is recommended that information in this report be integrated into mission planning documents.

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Future endeavors in space will be shaped by the concept of extraterrestrial surface bases. The lunar environment presents an extraordinary challenge in designing equipment and machinery to operate during lunar exploration missions and to construct a lunar base or early outpost. Because familiar terrestrial machines are so large, it is prohibitively expensive to move them to the moon. Also, they could not accomplish all the required work tasks. The objective of this study was to create conceptual models of equipment and machines suitable for operation on the surface of the moon.

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FOREWORD

This study was conducted for the National Aeronautics and Space Administration (NASA) under Reimbursable Order No. T9747P, dated March 1989. The NASA technical monitor was Mr. Barney Roberts, Office of Exploration (IE2).

The work was performed by Pacer Works, Ltd., Atlanta, Georgia, for the Engineering and Materials Division (EM) of the U.S. Army Engineering Research Laboratory (USACERL) under contract No. DACA 88-89-C-0011. The contract monitor was Mr. Alvin Smith. Dr. Paul A. Howdyshell is the Chief, USACERL-EM. The USACERL technical editor was Gloria J. Wienke, Information Management Office.

COL Everett R. Thomas is Commander and Director of USACERL, and Dr. L.R. Shaffer is the Technical Director.

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1 INTRODUCTION

Background

The lunar environment presents an extraordinary challenge in designing equipment and machinery to operate during exploration missions. Translating familiar terrestrial machines, such as a bulldozer, a truck, or a crane to the lunar environment would result in an inordinately large and thus prohibitively expensive launch mass. Also, adapted terrestrial machines may not be able to accomplish all of the required tasks since their articulation and control would be likely to be more difficult than a machine especially designed for a task. This study undertakes a review of the required lunar tasks and the technologies required to develop, on a top level conceptual basis, a candidate set of equipment and machines. In the final analysis, the optimum system will result only from close cooperation between the designers of the flight vehicles, construction equipment and machinery, and the facilities and infrastructure.

New technologies and emerging construction processes (e.g., using sulfur as a binder for lunar concrete[1]) illustrate the need for versatile and adaptable equipment. Although existing equipment should be available to support the construction process, new equipment will be needed. Development of machinery that can be adapted to work with a variety of new implements and accomplish new tasks will eliminate the need to supply dedicated single-purpose equipment for each process as it is added during expansion of a lunar base or early outpost.

Characteristics of the lunar environment affecting machines that are excavating, loading, hauling, and dumping lunar regolith (very hard and compacted rocky debris) are summarized in other sources.[2]

Objective

The objective of this study was to create conceptual models of equipment and machines suitable for operation on the surface of the Moon during construction of an outpost or early lunar base. The models are intended to perform the specified tasks at an acceptable productivity rate under both the circumstances established by the mission and the environmental conditions.

Scope

The scope of this study is limited to those scenarios identified by the National Aeronautics and Space Administration (NASA) for consideration in the FY 89 Lunar Evolution Case Study (LECS)[3] and

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[1] Raymond Leonard and Stewart W. Johnson, "Sulfur-Based Construction Materials for Lunar Construction," *Engineering, Construction, and Operations in Space: Proceedings of Space 88*, Albuquerque, NM, August 29-31, S.W. Johnson and John Wetzel, Eds. (1988), p 125.

[2] Leonard E. Bernold and Shankar Sundareswaran, "A Study on the Mechanics of Lunar Excavation," *Proceedings of One-Day Seminar on Planetary Excavation* (University of Maryland, College Park, MD, September 8, 1989).

[3] *Exploration Studies Technical Report, FY89 Status, Vol III: Planetary Surface Systems*, Technical Memorandum (National Aeronautics and Space Administration [NASA], Office of Exploration [OEXP], 1989).

the *Report of the 90-Day Study of the Human Exploration of the Moon and Mars*[4]. Although this scope seems rather narrow, it yields concepts and first-cut criteria that should be applicable, with appropriate scaling adjustments, to the whole range of missions in which similar activities will be conducted.

Approach

Major drivers, or parameters, in the design effort include functionality, reliability, repairability, and launch mass, which significantly influence the system cost. The tasks identified by a variety of sources (see cited and uncited reference section) to be accomplished by the equipment provided a guide to loads, work envelopes, productivity, and other requirements that must be met. Terrestrial machines and lunar machines presented in other space exploration papers and reports were reviewed for applicability, either as a complete machine, or as a contribution of some useful component. Because a suitable set of machines that met all criteria was not found, it became evident that new concepts were required.

The requirements for equipment structure, mobile power, and teleoperation were then used to develop estimated masses of the machines and accessories.

The strategy used in creating conceptual designs was to start with a "clean slate" and strive to clearly and accurately define each problem before undertaking the development of a conceptual design solution. The intent was to leave every opportunity open to an innovative solution that might yield or lead to the optimum solution. The preconceived notions that ordinarily present barriers to other solutions were set aside initially, then reintroduced when the evaluation or trade study portion of the process began. The resulting designs have terrestrial equipment experience in their heritage but were not unnecessarily constrained by it.

A number of machine configurations are available or could be developed to accomplish a given list of tasks. Three were investigated in this study and are briefly described as:

1. A single machine capable of accomplishing all tasks.

2. A set of single-purpose or dedicated machines.

3. A plurality of identical mobile work platforms with a modular set of interchangeable implements or attachments.

[4] *Report of the 90-Day Study of the Human Exploration of the Moon and Mars*, Johnson Space Center, (NASA, November 17, 1989).

2 TASK DEFINITIONS

The elemental construction tasks listed in Table 1 were developed in cooperation with the U.S. Army Construction Engineering Research Laboratory (USACERL), NASA, and the machine designers at Pacer Works, Ltd., Atlanta, GA. Names of the elements and their reference designations established in other works[5] have been used in this report for consistency. Here, the construction tasks have been arranged under machine or implement categories (shown in bold faced type). This arrangement is arbitrary and serves only to provide a lead-in to subsequent discussions in this study.

Table 1
Task Definitions

Elemental Task Name	Unit of Work	Productivity
MOBILE WORK PLATFORM (D)		
Excavate	volume, m^3	3 m^3/hr
Remove boulder	pieces	4 pieces/hr
Break-up large boulders	pieces	.25 pieces/hr
Trench	volume, m^3	3 m^3/hr
Grade	volume, m^3	3 m^3/hr
Backfill	volume, m^3	6 m^3/hr
Off-load pallets	pallets	.2 pallets/hr
Emplace large pieces	pieces	.2 pieces/hr
Emplace medium pieces	pieces	2 pieces/hr
Emplace utilities	length, m	500 m/hr
Set anchors	points	1 point/hr
Elevate bulk cargo	volume, m^3	3 m^3/hr
Transport crew	distance, km	10 km/hr
Restation machines	distance, km	4 km/hr
CARGO BIN (C)		
Remove boulders	pieces	4 pieces/hr
Transport bulk cargo	volume, m^3 distance, km	2 m^3 @ 4 km/hr
Transport pallets	distance, km	1 km/hr
Restation machines	distance, km	4 km/hr
CASTERS (E)		
Remove boulders	pieces	4 pieces/hr
Transport bulk cargo	volume, m^3 distance, km	2 m^3 @ 4 km/hr
Transport pallets	distance, km	1 km/hr
Transport crew	distance, km	10 km/hr
Restation machines	distance, km	4 km/hr
CRANE ASSEMBLY (F)		
Offload pallets	pallets	.2 pallets/hr
Emplace large pieces	pieces	.2 pieces/hr

[5] Bell, Lisa, and Walter Boles, *"Operations Analysis for Lunar Surface Construction: Results from Two Office of Exploration Studies,"* Report to the U.S. Army Corps of Engineers (April 1990).

Table 1 (Cont'd)

Elemental Task Name	Unit of Work	Productivity
REVERSE CLAMSHELL (G)		
Excavate	volume, m^3	3 m^3/hr
Trench	volume, m^3	3 m^3/hr
Backfill	volume, m^3	6 m^3/hr
Elevate bulk cargo	volume, m^3	3 m^3/hr
DRILL IMPLEMENT (H)		
Break-up large boulders	pieces	.25 pieces/hr
Set anchors	points	1 point/hr
REGOLITH BAGGER (I)		
Elevate bulk cargo	volume, m^3	3 m^3/hr
ROBOTIC ARM (J)		
Remove boulders	pieces	4 pieces/hr
Emplace medium pieces	pieces	2 pieces/hr
Emplace utilities	length, m	500 m/hr
GRADER BLADE (K)		
Grade	volume, m^3	3 m^3/hr
SUPERVISORY MODULE (L)		
Participates in all tasks	N/A	N/A

3 EQUIPMENT AND MACHINES

General

The machine concepts presented in this report share a number of common design drivers and issues of concern. The designs were based on the assumption that the flight and operations schedules set forth in the NASA scenarios would be met and that the design "freeze" would occur far enough in advance of these schedules so that test and evaluation of components and subsystems could be conducted in lunar surface simulating test beds. It was also assumed that the earliest machines would not have the timely advantage of detailed engineering knowledge of soil/machine interactions, for instance, with any great certainty. The direction has been to create robust designs that can accommodate a reasonable degree of uncertainty. The required technologies appear to be available now or would be available to meet the design freeze dates. One exception may be the control systems; but this field is developing rapidly. Control system design reasonably could be frozen for design at a late date.

Systems Issues

A variety of issues exist that affect considerations in conceptual design of equipment. In many cases it is not practical to rank order the issues since circumstances of use are almost certain to affect the order. Thus, some issues that must be considered are presented in subsequent sections.

Fasteners and Fastening Systems

The types of fasteners and fastening systems suitable for the lunar environment are extraordinarily limited when compared to those presently available for terrestrial use. Even those used for orbital spacecraft might not be useful when exposed to lunar dust. Robotic assembly and disassembly considerations further restrict the suitable choices.

One of the most difficult fasteners to deal with robotically in the lunar environment is the threaded bolt used with a nut or tapped hole. For example, starting a bolt into a tapped hole requires that the end of the bolt be precisely located in the x, y, and z coordinate directions and that the bolt centerline be aligned properly with each of the three axes. Then the bolt must be translated and rotated simultaneously to follow the helical path of the thread. Any force or torque applied in the lunar environment will cause both machines to shift, causing some degree of misalignment. Sensing the various dimensional and angular relationships before and after the thread is started will be difficult, especially in confined spaces. Installation torque must also be limited to avoid catastrophic failure of the bolt. If an excess torque is indicated, the challenge will be to determine if the cause is cross-threading of the bolt, dust contamination, microscopic surface welding, thermal distortion, or some other cause.

Particular attention must be paid to the fastening of soil engaging tools and associated support structures. These items are expected to be subjected to considerable shock, vibration, and variation in temperature. In some cases, the abrasion due to the relative motion with the soil will also deteriorate the performance of the fastener or interface with the robotic servicing operations.

The fasteners and fastening systems in every machine that will be maintained in this environment must be chosen on the basis of robotic servicing and maintenance.

Worksite Illumination

Whether by direct viewing or by an indirect means, such as a video system, the operator of the equipment must be provided with the appropriate level of illumination, suitable luminance contrast, and

the correct color of both the object of interest and the background. Lunar daytime illuminance can be up to 120,000 foot-candles[6], but that required for comfort and efficiency in medium-to-fine assembly operations should be between 100 and 500 foot-candles.[7]

Schedules that must be maintained to carry out the planned tasks will, in part, dictate Sun angles and reasonable access will dictate viewing angles. Features of the lunar surface and nearby machines, equipment, and facilities will create both shadows and reflections to further influence or modify the illuminance of the object.

Compensations must be available to adjust the contrast, color, and intensity of the light reaching the object to put these factors within an acceptable range for the video equipment or for the astronaut's eyes. Using the Sun as a source of illumination requires attenuation and diffusion for ideal viewing. Color integrity is required so color-coded items or colors used to distinguish object features or functions can be accurately identified. A tent-like structure comprised of a frame and a translucent fabric is suggested where size and portability are practical.[8] Where low Sun angles are involved, a simple drape of translucent material would be useful.

An alternative to the translucent fabric is thin foil with small circular apertures sized and distributed as required to achieve the desired results by light diffraction technology. The function of each aperture would be similar to that in a pinhole camera. The pinhole camera technology is discussed in other literature.[9] Basically, incident light reaching the apertures in the foil is tspread by diffraction to form the emerging light. Deteriorization in optical and mechanical properties, due to long-term exposure to the lunar environment, must be considered for both fabric and foil, but a highly reflective metallic foil with appropriate apertures appears to be a reasonable candidate.

The textures and surface materials and coatings selected for the components of the machines are also important to ideal viewing. During the lunar night, various sources of illumination should be made available. The worksite for each machine will require both general and localized illumination for either video systems or direct viewing by astronauts. Battery powered sources, such as floodlights and spotlights, will require very little power and will be most efficient if their placement and orientation can be flexible. If dust on the lenses appears to be a problem, bare wire configurations should be considered.

Mobile Power

Perhaps the most critical technology issue affecting the design of mobile work platforms is that of power distribution. The power unit may be on board and rely on another system to recharge, refuel, or rejuvenate it. This method offers the mobility required to accomplish the variety of tasks needed to construct an early outpost. The two outstanding power-related constraints on the productivity of such a machine are the mass of the onboard unit and the resupply capability of the primary source.

Rechargeable batteries and regenerable fuel cells (RFCs) are favored for mobile power sources. Table 2 indicates the estimated onboard mass and volume required for the specific duty cycles shown. It is evident that the onboard power unit seriously constrains the design and performance of the mobile machine.

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[6] National Aeronautics and Space Administration (NASA) Space Systems Technology Model, TM 88174 (Office of Aeronautics and Space Technology, Washington, DC, June 1985).

[7] B.H. Kantowitz and R.D. Sorkin, *Human Factors: Understanding People-System Relationships* (John Wiley & Sons, New York, NY, 1983).

[8] E.M. Hatton, *The Tent Book* (Houghton Mifflin, Boston, MA, 1979).

[9] David Halliday and R. Resnick, *Fundamentals of Physics* (John Wiley & Sons, New York, NY, 1981), pp 722-725.

Mobile Power Unit Mass and Volume

Unit Reference Designation*	Power Unit Technology	Peak Rated Power kWe	Work Period Hours	Recharge Period, Hours	Duty Cycle % Work Period Time @ % Peak						On-Board Mass, kg	On-Board Volume, m^3
					Peak 100%	80%	50%	20%	Idle 0%	Downhill Breaking		
A	battery	.5	6	18	3	10	25	37	15	10	14	.008
B	battery	.5	6	6	3	10	25	37	15	10	16	.008
C	battery	1	6	18	10	10	15	40	10	15	28	.016
D	RFC	2	6	18	10	10	15	40	10	15	29	.26
E	RFC	3	12	12	5	20	45	10	20	0	88	.94
F	RFC	4	18	6	10	10	15	40	10	15	145	1.3
G	RFC	5	6	6	5	25	25	25	20	0	116	0.83
H	RFC	5	12	12	10	10	30	30	10	10	125	1.4
I	RFC	10	6	18	10	10	15	40	10	15	145	1.3
J	RFC	10	12	12	2	10	18	40	20	10	174	1.9
K	RFC	20	6	18	10	20	15	40	10	5	360	3.3
L	RFC	40	6	18	30	20	30	20	0	0	1127	10.2

* Designations used refer to this table only and not to other lettered entities in this report.

Arbitrary load power levels and estimated duty cycles were used to establish representative power requirements for Table 2. Onboard mass and volume calculations were conducted for battery and RFC technologies for each power requirement in Table 2. It should be noted that Table 2 is a constructed reference table used to facilitate estimation of volume and mass of a mobile power system based on power requirements. The most favorable onboard mass was used to determine the technology applicable to each case. The peak demand, the integration of the time at each power level (% Peak), and the total time available for recharge, collectively drive the design of each power unit. Waste heat management system components are not included, but would have to be considered and the overall power plant adjusted to compensate for disposal of low grade heat. As a sample from Table 2, Figure 1 shows a duty cycle integrated over time between recharge cycles.

Using unit "J" from Table 2 as an example, the mass is estimated at 174 kg for a unit having a 10-kilowatt electric (kWe) peak power capacity. A 10-kWe machine operating on the lunar surface compares, in terms of power, with a terrestrial garden tractor rated at 13 horsepower.

Another relationship in mobile power is indicated by Figure 2, which is a representative sample of the power/weight ratio for terrestrial excavation equipment.[10] The data indicate that the relationship between the weight of the machine and the power required to make the machine effective in excavation operations is close to linear. For this sample series of bulldozer models, the maximum achievable drawbar pull is roughly equal to the weight of the machine.

Taking this further by assuming the same force is required to doze the lunar soil as to doze terrestrial soil, the gravity force (weight) on the Moon must be the same as that on the surface of the Earth. The mass requirement is then six times as great. Checking the curve in Figure 2 for a bulldozer six times as heavy as the first case (say 15 tons), the weight required is then 90 tons, but the power requirement is still 100 kWe. Further assuming that this can be scaled downward linearly an order of magnitude, the result is a 9-ton machine having a 10-kWe power unit and one-tenth the productivity of a small terrestrial bulldozer. The 9-ton mass is still far greater than allowed by the scenarios for a machine performing this task. It is obvious that such a terrestrial-to-lunar translation would be unreasonable.

It also follows that a 100-kWe machine is out of the question and that productivity expectations based on a small terrestrial machine would be reduced accordingly. The traction limitations of a bulldozer, directly related to gravity force and indirectly related to onboard power, further constrain its productivity.

In the initial phase of construction, the stationary power supply for the entire outpost is expected to have a capacity in the 12- to 50-kWe range. Recharging of 10-kWe rated mobile machines from this source represents a substantial demand. It would be impractical to recharge a 100-kWe rated machine from such a source.

A workshop on extraterrestrial mining and construction[11] considered power distribution to large equipment to be the most critical issue affecting mobile equipment design.

Grading

Grading, leveling, and trenching tasks will involve the displacement of loose-to-compacted soil and small-to-moderate size rocks that might be loose or tightly embedded in the compacted soil. Penetration

[10] *Caterpillar Performance Handbook* (Caterpillar, Inc., Peoria, IL, October 1988).

[11] *Proceedings of the FY89 Workshop on Extraterrestrial Mining and Construction*, Bridget Register, Ed., Golden, Colorado, May 2-4, 1989 (Lockheed Engineering and Sciences Co., April, 1990).

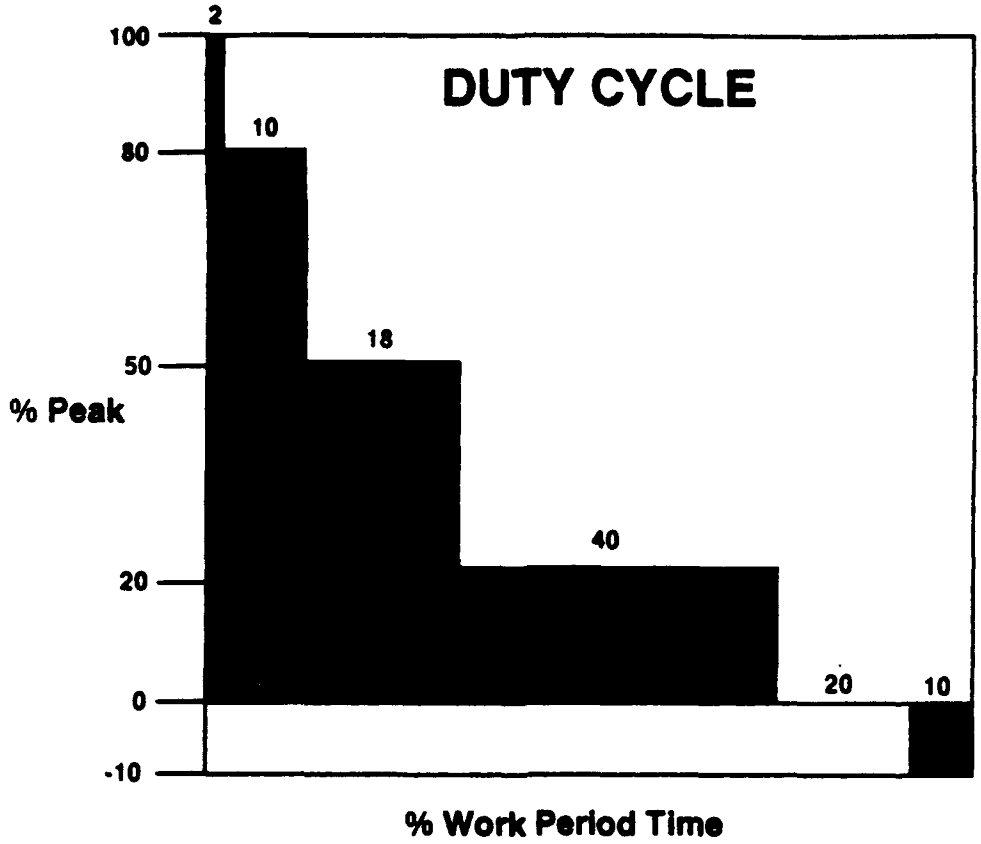

Figure 1. Sample duty cycle.

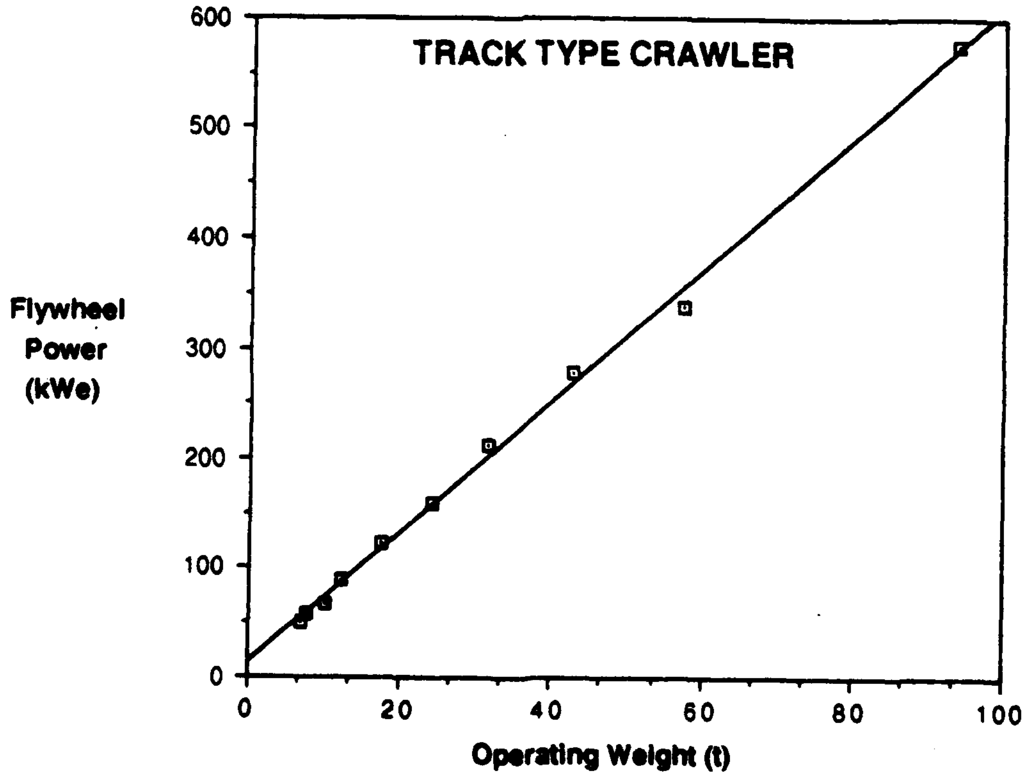

Figure 2. Power/weight ratio for terrestrial excavation equipment.

of the soil engaging tool depends on the normal (gravity) force. The scooping or dozing force depends on the horizontal force developed by the machine's traction. This traction is again dependent, in part, on the gravity force imposed on the traction device (wheel, foot, or track) by the weight of the vehicle. Due to the size and limited mass of the machine, and the 1/6 gravity at the lunar surface, the normal force available both for traction and penetration (and they must share the total between them) is so small that the techniques are not expected to be useful for any function but moving loose material. A rotary flail that acts as a centrifugal pendulum is suggested.[12] Although designed to reduce residues on tree farms, the flail would work by imparting the stored energy to the rock to fracture it effectively.

Thus, the strategy must be to design an excavation machine that is perhaps an order of magnitude better than the direct terrestrial, scaled approaches. The use of opposite and equal reaction excavation devices offers one possibility; the digging forces are reacted within the digging device, its immediate structure, and actuator(s). Such large forces are then not required of the traction device and the main structure of the machine is not required to transmit them. A wire brush-like excavator has been suggested[13] as another device requiring a minimum of normal and tractive forces.

Boulder Removal

A detailed subsurface survey should precede the excavation of foundations, trenching, or other such cuts to avoid boulders too large for the machinery to handle. If an alternate site is not available, the oversized boulder must be fractured for removal.

If explosive methods are acceptable, holes for the charges must be made with a rotary percussive drill unit positioned by the mechanical arm. Using another end effector, the arm would be used to set the charges.

Instead of explosive charges, the arm can insert electrically heated rods or a set of feathers and wedges to be driven by the percussive mode of the drill. A crane can be used to hoist and release a drop ball (wrecking ball) to fracture the rock. The lunar gravity and limited available drop height together diminish the practicality of this simple method.

Bearings

Motors, linkages, pivotal joints, etc. will be components having relative motions within the work machines. These and other relative motions will be accommodated by bearings of various forms such as continuously rotating, oscillating, and reciprocating. The combined environment of temperature extremes, abrasive dust, and hard vacuum all but preclude the use of conventional rolling element bearings. Seals must flex to be effective in excluding microscopic dust from the inner portions of the bearings as the machine works at its assigned tasks. Materials having the required flexibility over the entire temperature range, adequate abrasion resistance to the dust, and hard vacuum tolerance over an extended life cycle are not available.

An alternative to using a seal to exclude dust is to use superhard materials as bearing tribological surfaces. Seals would not be used and any dust or other foreign material would be ground between the hard surfaces. Effective friction coefficients between the superhard materials is not well established for

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[12] C.F. Cammock and M. Lambert, *Parameters for the Design of Efficient Forest Residues Reduction Machinery* (Forest Service, U.S. Department of Agriculture, San Dimas, CA, December 1976).

[13] Walter Boles Personal Communication, Department of Civil Engineering, Texas A & M University, College Station, Texas, July 1989.

vacuum environments, but they could be high. Microscopic beads of glass or other moderately hard, chemically inert materials might be injected to exclude dust and to function as a lubricant.

Both coatings and monolithic forms of superhard materials have been used in terrestrial bearing applications[14] but often involve the use of some kind of fluid between the elements. Bearings coated with or comprised of superhard materials are particularly attractive in drilling and other equipment that will be exposed to dust under pseudohydrostatic pressure.

Tool Wear

The soil engaging tools and their replaceable cutting edges are expected to wear as they dig and move the soil. If they are made of abrasion-resistant steels or alloy steels with abrasion-resistant coatings, as are their terrestrial counterparts, servicing and resupply will be difficult and costly. To extend the useful life of the cutting edges, superhard materials such as diamond-like coatings can be applied. This emerging technology is being used in limited terrestrial applications[15] and is potentially useful in lunar operations. Additional investigations are needed to determine the mechanical and tribological properties of candidate and superhard materials in a simulated lunar environment. The extreme properties of these materials (i.e., hardness, smoothness, and thermal conductivity) make them attractive as wear-resistant surfaces.

Navigation

Dust may be expected to interfere with the lenses of video cameras used for navigation or any other use.[16] Pinhole camera technology may provide some relief, but other spectra such as radar could be used. For machines that operate only in the vicinity of the base, a beacon system will be useful in machine location but not in situations where precise operations are performed.

Analysis

Representative tasks and associated activities, along with rough estimates of the times required or productivities, have been stated in Chapter 2. Some of the prominent systems issues likely to be involved in accomplishing the tasks were described earlier in Chapter 3, and reasoning or rationale for considering them as issues were given.

A detailed analysis to justify size, speed, control, structure, and power required to carry out the tasks at the productivity levels suggested is very impractical at the present time. At best, only engineering judgment and guessing comprise the basis of the tasks. The limited data available combined with first principles are the only guides for formulating both the parameters and the attempts in translating from terrestrial experiences to lunar environmental constraints. In other words, the guesses and assumptions are probably good, but it is almost a certainty that any attempt at rigorous analysis would be bad.

Given the assumptions of tasks and productivities, it is possible to conceptualize some construction equipment resources that could be used to carry out these tasks.

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[14] National Research Council, Committee on Superhard Materials, *Status and Application of Diamond and Diamond-Like Materials: An Emerging Technology* (National Academy Press, 1990).

[15] National Research Council.

[16] Apollo 15 Mission Report, Hearing Before the Committee on Science and Astronautics, House of Representatives, Ninety-Second Congress (U.S. Government Printing Office, September 9, 1971).

Resources

The resources (machines or implements) described and discussed in the following paragraphs are listed in Table 1 and relate to the tasks identified therein. Prime movers or work platforms are discussed first followed by mobility units and a series of implements. Note that the implements are task specific and may be used with any of the platforms.

Mobile Work Platform (D)

Several mobile work platform configurations are described in the following paragraphs. They share common features, but differ in their mobility modes and work envelope capabilities.

SKITTER. The fundamental machine, nicknamed SKITTER, that can serve both as an automotive device and dexterous carrier for a variety of implements and attachments is shown in Figure 3. It is comprised of a central body and three equally spaced legs, each of which includes a powered hip joint, a femur, a powered knee joint, and a tibia that terminates as a foot. Its walking mode includes a number of gaits and variable step sizes. The fundamental step is accomplished by one leg pushing against the surface, generally rotating the body and other two legs about the line joining their feet. This rotation continues due to inertia and causes the foot to be raised from the surface. While this foot is off the surface, the hip joint, knee joint, or both can impart a radial motion to the foot. Also, while the foot is off the surface, the joints in the other two legs can be reconfigured (angular rotation) to cause a generally tangential motion of the raised foot. If either or both of these motions take place while the foot is off the surface, it will return to the surface by gravity force at a new position. By repeating a similar action at the second, then third foot, a net lateral motion of the machine relative to the surface results. With such sequential steps, the machine can walk in any radial direction, rotate about any point on the surface, or some combination of both for motion along a curved path. The machine is quite simple mechanically because it has only six moving parts, plus six actuators. The SKITTER has been built and demonstrated.

SCAMP. This platform is a wheeled vehicle that uses its struts as an active suspension system. It is comprised of a central body, three articulated struts, and three caster units as shown in Figure 4. It features self-stabilizing, self-powered caster units attached to each of the struts by means of a spherical joint located below the axle centerline.

The body is equipped with an interface at the top and another at the bottom for the attachment of implements or cargo. While connected to an implement, the machine can act as a dexterous carrier and provide up to six degrees of freedom for manipulation of the implement or cargo.

The lower interface can also be used to handle containerized or palletized cargo and materials or to handle science packages and similar items. The six degrees-of-freedom adjustability is useful in attaching to the cargo and in setting the cargo down. Within its range of motion and work envelope, this adjustability can be used in performing assembly tasks. Access to the assembly task would be limited by the position and space occupied by the struts and casters. To be handled by the lower interface, the cargo must be equipped with the matching interface, just as the implements do.

Surface conformity is achieved by virtue of the tripod nature of the entire device and is enhanced by the ability of the caster units to pivot and adapt to wheel-to-wheel surface irregularities.

The adjustable nature of the three struts allows for both surface adaptability and appropriate work task configurations. The caster units each have their own power supplies and each wheel is driven by a separate motor. Each wheel is controlled separately, but in conjunction by telemetry signals. Inherent stability and surface conformability of the caster is provided by attachment to its strut by means of a spherical joint centered between the wheels and located below the axis of wheel rotation. The added

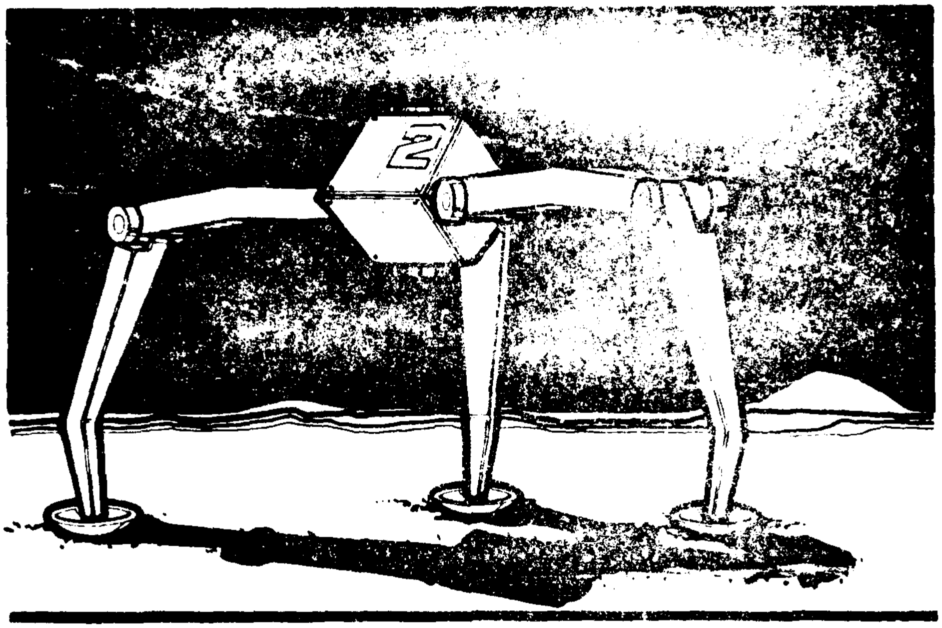

Figure 3. Mobile work platform - SKITTER.

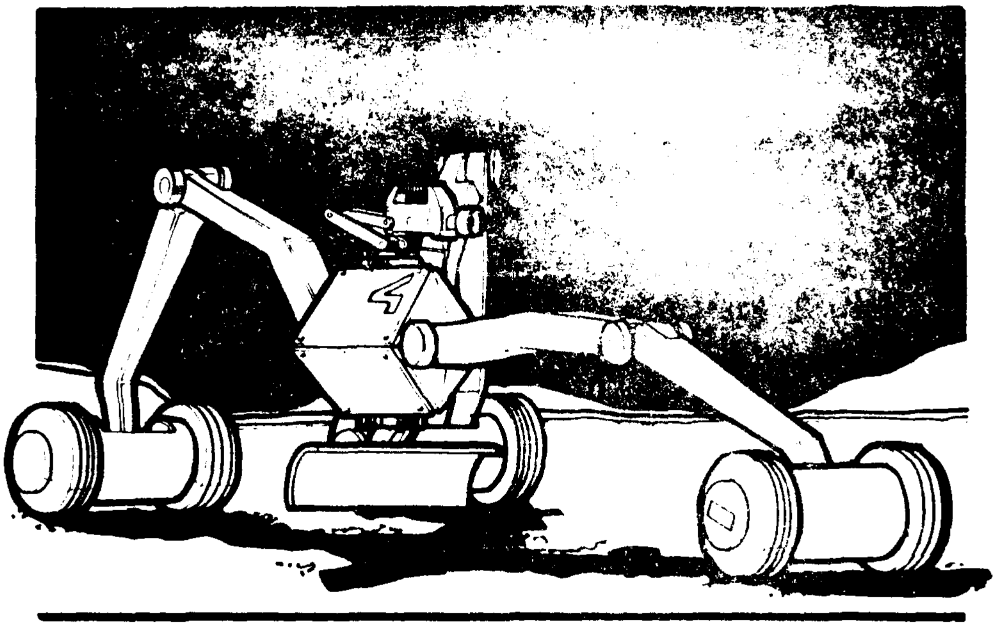

Figure 4. Mobile work platform - SCAMP. (Shown with grader blade mounted to the lower implement interface.)

surface conformity comes from the ability to raise or lower a single strut and also from the ability to change track width, wheelbase, and surface clearance as needed. Working configurations come both from the adjustability of the struts and from the ability to orient the caster units for travel in any given direction.

Adjusting the wheelbase changes both the natural frequency of the vehicle structure and the coupling relationship between the surface and the vehicle. This feature may be used to minimize vibration and bouncing while the vehicle is in motion.

An example of work task adjustability is illustrated in Figure 4 where a grader blade is attached to the underbody of the central frame. Here, strut joint motion provides blade height adjustment and tilt (roll) angle adjustment. Blade yaw control is accomplished by reorientation of the wheel path with respect to the frame and blade. Thus, the adjustability of the entire device not only allows it to follow irregular surfaces, but uses the existing mechanisms for the degrees-of-freedom necessary for the blade to generate the desired smoothed and/or leveled surface.

The vehicle is fault tolerant in that even if a power failure occurred in one or two caster units, both traction and steering of the system could be maintained by the remaining caster truck unit. Likewise, a failure in any one or two of the six strut actuators could still allow useful adjustability to be maintained by the remaining actuators.

Caster units provide the favored mobility mode for this vehicle. The caster units on SCAMP (described in more detail in the literature[17]) are two-wheeled and are connected by a spherical joint at the end of the tibia. The wheels are independently driven so steering of the caster unit is accomplished by relative motion between the wheels. Coordinated motion of the three casters establishes the direction in which the entire vehicle moves. In the wheeled mobility mode, the vehicle can move in every radial direction or rotate about any point. In traversing an unprepared path, it is useful to have the capability of modifying both the wheel track and wheel base. The machine has this capability, and can also adjust to out-of-plane relationships among the caster units and struts, to keep the body vertical during sidehill travel as an example. The spherical joint also allows the limited wheel-to-wheel adjustment for surface conformity. This action is similar to that of a bogie suspension except the caster unit adjusts for lateral variations instead of longitudinal variations.

Rolling resistance generally increases with load, but this relationship is nonlinear. Thus, to achieve minimum rolling resistance for a given vehicle having identical wheels, the load must be uniformly distributed. This optimum condition is closely approached in this machine by the combination of two features. First, the caster units are symmetrical and are connected to their strut's load at the midpoint between them, so they share this strut load equally. Second, the triangular relationship of the struts tends to distribute the load of the vehicle uniformly among the struts. For travel on a level surface, the struts would be arranged symmetrically so the spherical joints are located in an equilateral triangle as viewed from above.

Traveling uphill or downhill, two caster units would be side by side at the lowest part of the slope. Sidehill travel would suggest that one caster follow another along the lowest line of the slope. To prevent overturning on the slope, the gravity vector, through the center of gravity, must fall within the triangle formed by the three spherical joints. Travel along any slope then suggests that this triangle be as large as possible, that the body be as low as possible and that a single caster be as far to the uphill side as possible.

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[17] James W. Brazell "Planetary Surface Systems Truck," *Proceedings of Space 90: Engineering, Construction, and Operation in Space II*, Albuquerque, NM, April 22-26 (American Society of Civil Engineers [ASCE], 1990).

Underbody clearance is adjustable and can be from zero to nearly equal to the extended strut length. Clearance under each caster is more limited, but presents only a narrow gap between the wheels. Judicious path selection to avoid impeding obstacles will be required.

Fault tolerance with respect to caster wheel power failure is available at several levels. Loss of power to one wheel requires that the companion wheel not be powered. The caster companion unit would then trail in caster fashion since the rolling resistance would cause the axle to trail the spherical joint. Failure of another motor on a second caster would have the same effect as in the first case and would also cause loss of control of orientation with respect to the travel path. With only one truck powering the vehicle, this caster would lead on a flat surface. Sidehill travel would result in the two unpowered casters traveling with a tendency towards the lower side of the slope. On a downhill slope, these two casters could lead the powered caster as it retards the motion down the slope. If a motor fail in the third caster, the machine could use the walking mode for mobility. This would be cumbersome because of the loose truck units.

If one caster unit becomes stuck in a small depression, the body can be lowered to the surface and the strut can lift the caster and set it down in a new position.

LEVPU. The technology supporting the conceptual design of a "Super Crane" or Lunar Excursion Vehicle Payload Unloader (LEVPU) includes a gantry crane (described in other literature[18]). This gantry crane was used to load trailers onto railroad piggyback flat cars and shares the features of:

- Load straddling
- Six degree-of-freedom manipulation of the load
- A clamp (end effector) for grasping the load
- Surface conformity (to a substantially lesser degree)
- Independently driven wheels, and
- Coordinated steering of wheel pair sets.

This 50-ton capacity gantry crane weighed approximately 60 tons, thus had a 1.2:1 ratio of weight to payload.

Trailer loading required precise handling as the trailer's pin was connected to the "fifth-wheel" stanchion on the railroad car. Position error tolerances were in the order of 0.5 in. (1.27 cm) vertically, 2 in. (5.0 cm) laterally, followed by a 4- to 10-in. (10.16- to 25.4-cm) forward motion to latch the hitch. The trailer's rear wheels could only be out of position laterally about 4 in. (10.16 cm). Productivity in the loading of trailers was less than 3 minutes each. Unloading of the trailers was slightly faster on average since placement at the end of movement did not generally have to be as precise as in loading.

The surface conformity and adjustability features of the LEVPU are traceable, in part, to common portable tripods used with cameras, telescopes, and surveyors' instruments.

Though illustrated in other literature[19] in a walker form, it is obvious that the conformity and adjustability features would follow the wheeled arrangement shown in NASA's 90-Day Study report.

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[18] United States Patent 3,645,406, *Gantry Cranes* (U.S. Government Printing Office, Washington DC, February 29, 1972); Martin J. Robarbs, "A Giant Toils at Tilford," *L & N Magazine*, Vol 44, No. 2 (Louisville and Nashville Railroad, Louisville, KY, February 1968).

[19] David J. Bak "A Visit to the Lunar Outpost," *Design News*, Vol 43, No. 7 (April 6, 1987); and David J. Bak "Three Legs Make Mobile Platform," *Design News*, Vol 44, No. 4 (February 15, 1988).

The LEVPU is a seriously compromised design, but was formulated to satisfy the single machine requirement of the 90-Day Study scenario. A single point failure might preclude its function until repairs were possible. It unloads the highest, heaviest cargo from above, so it must accommodate essentially parallel load paths. This adds substantially to its mass. The preferred method of lifting is from below or at least along the ends or sides of the large items of cargo.

Jacks. Another use of the caster units is in conjunction with relatively large structures in the role of a powered caster. Figure 5 shows a beam and column arrangement that forms a jack that can be used in pairs to unload a habitat from a lander, then transport the habitat to a site and set it on its own supports. As with the mobile work platform, the caster units, jacks, and habitat together constitute a vehicle that can travel in any radial direction, rotate about any point, or a combination of the two to travel along a curved path. In this configuration, the motion for placement or assembly to other structures is limited to vertical travel, pitch, horizontal translation, and rotation. (i.e., five degrees-of-freedom).

For irregular surfaces, traction requirements must be met by three of the caster units and each caster unit must support at least one-half of the load.

OPUS. Dissatisfaction with the caster units as applied to the SCAMP and LEVPU machines served as the motivation to create the OPUS concept. Figure 6 shows the tubular sector joint created as an alternative to the free ball joint connecting the caster unit to the strut. An even simpler single wheel version, represented by Figure 7, offered the potential of using the wheel as a footpad for a walking mode. Similar sector joints were then applied to the struts in place of hinged or telescoped joints on the previous mobile platforms.

The platform provides mobility, manipulation, and power for a variety of interchangeable implements to accomplish the required tasks. The vehicle is comprised of a central body and struts that each terminate in a wheel. Each strut includes a hip joint, a femur, a knee joint, a tibia, an ankle joint, and a wheel. Two particularly favorable configurations are shown in Figures 8 and 9. The first uses three struts mounted equally spaced around the body. The other is a six-strut configuration having three struts along each side. Potentially, two three-strut machines could be merged to form a six-strut configuration. The ankle joint, made of rotatable oblique tubular sections, provides steering and alignment of the wheel which is driven by the last section. Reorientation of this joint places the wheel in a horizontal position as a footpad for the walking mode of mobility. The hip and knee joints are similar in construction to the ankle joint. This arrangement provides struts having tubular structures which approach the ideal cross-section for strength/weight and stiffness/weight ratios in bending and torsion. The vehicle, as conceived, uses design principles that include mechanical simplicity, fault and accident tolerance, minimal mass, commonality of parts, adaptability to mission changes, and control by microprocessors which use uploadable, task specific software. A version of the vehicle with as few as three struts (Figure 8) would have both forms of mobility, but lack the redundancy and the ability to drive implements directly that may be seen in the six-strut version. The six-strut vehicle not only provides dexterity and power for the associated implements, but can essentially emulate the rolling mobility of the familiar six-wheel drive vehicles or, in the walking mode, emulate the mobility of the familiar six-legged walking machines.

Figure 10 shows a six-strut version of the vehicle with rolling wheels. By simple rotation of the ankle joint, each wheel can become a horizontal footpad, converting the vehicle into a six-legged walking machine (Figure 9). This machine, in the six-strut form, is the preferred embodiment of the platforms presented here. It is described in more detail in other literature.[20] One or two wheels can then be raised to capture and drive work implements leaving the balance for rolling or walking mobility (Figures 11 and 12).

[20] James W. Brazell and W. M. Williams, Jr., "Omnidirectional Platform for Unstructured Surfaces," *The Case for Mars IV Conference*, University of Colorado, Boulder, CO, June 4-8, 1990.

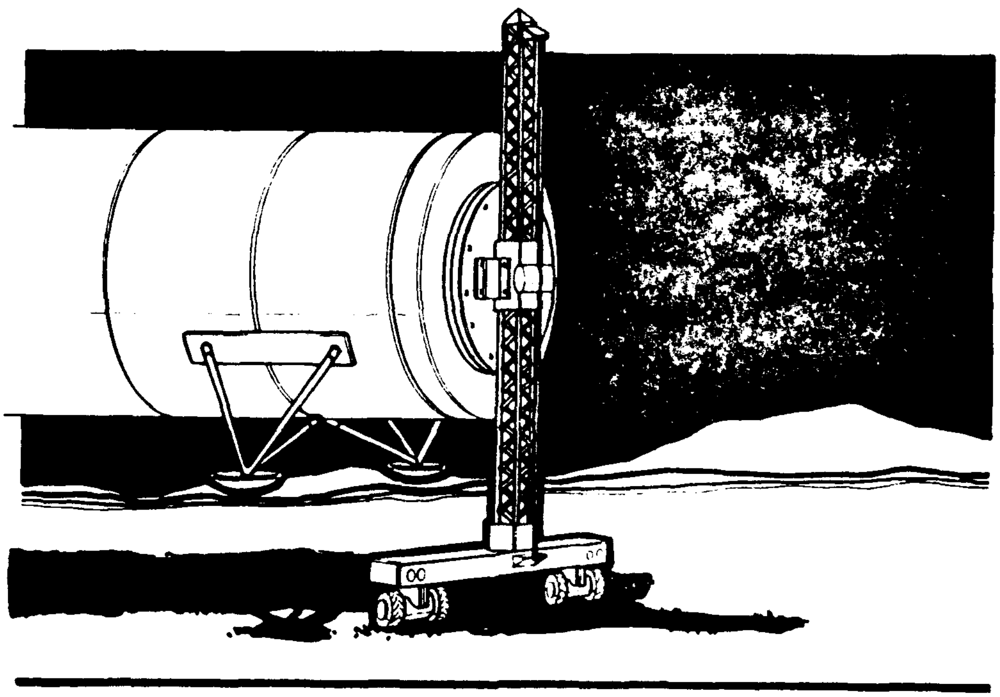

Figure 5. Jacks with casters attached to a habitat for unloading, mobility, and emplacement.

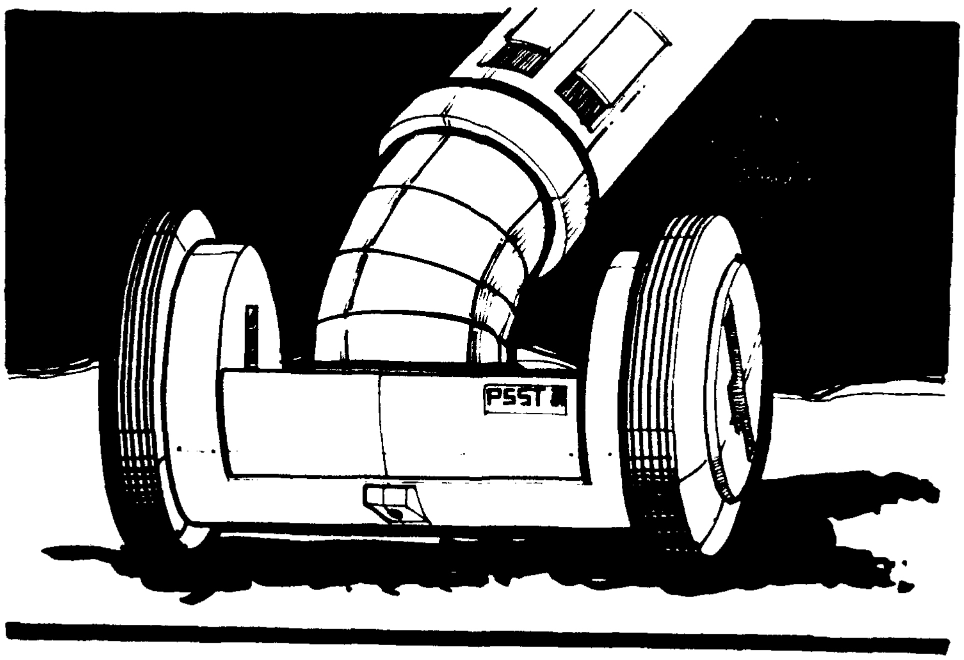

Figure 6. Dual wheel caster with tubular sector joint.

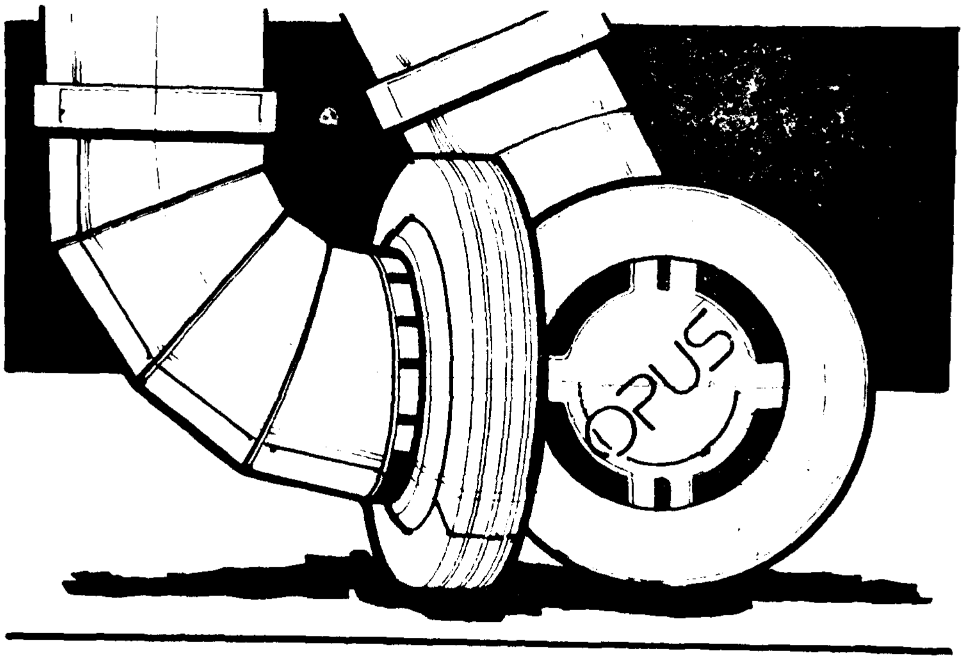

Figure 7. Single wheel adapted to strut.

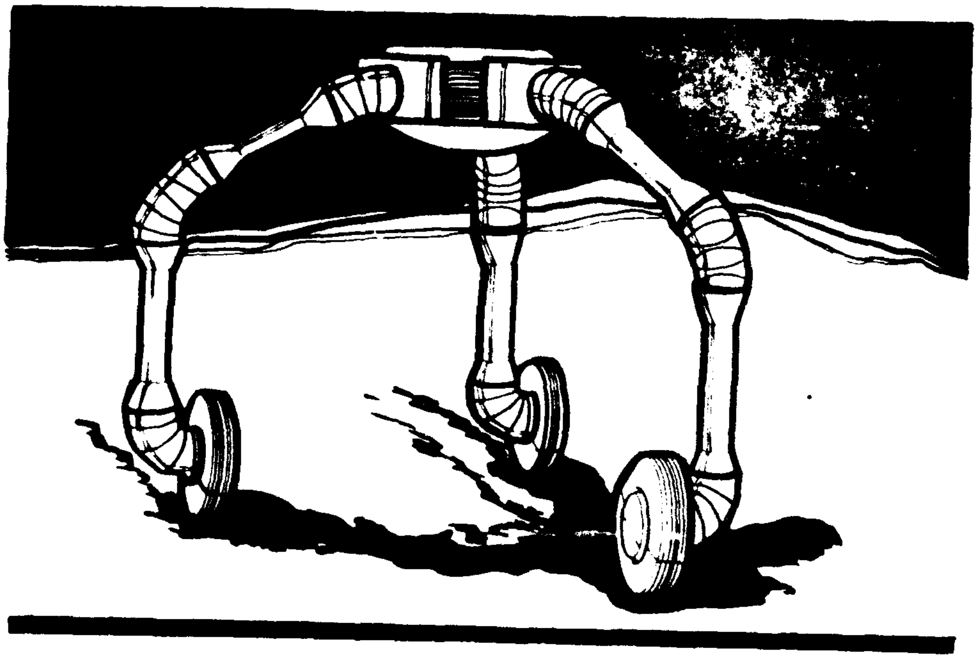

Figure 8. Three-strut machine in rolling mobility mode.

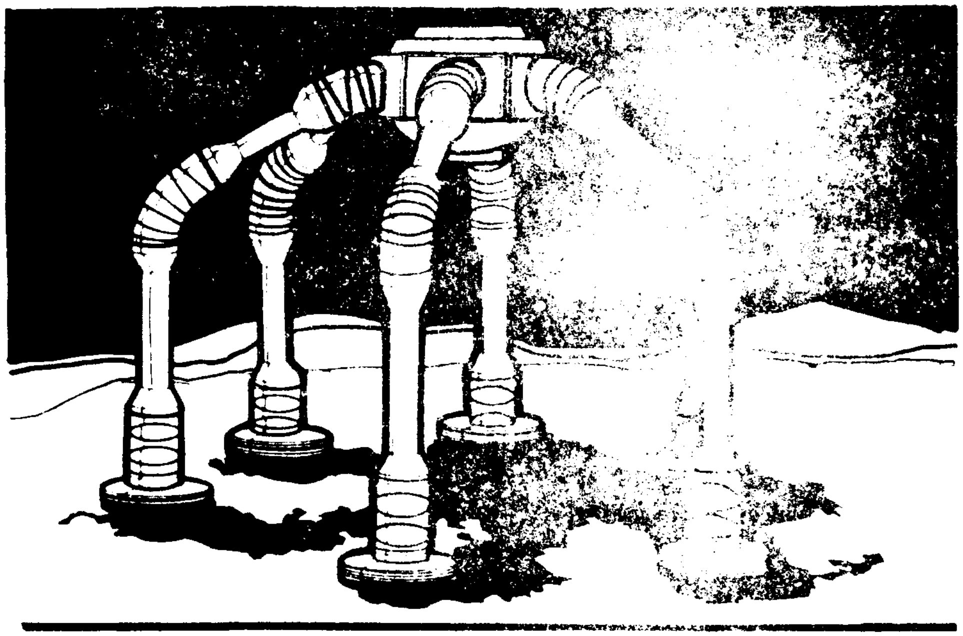

Figure 9. Six-strut machine in walking mobility mode.

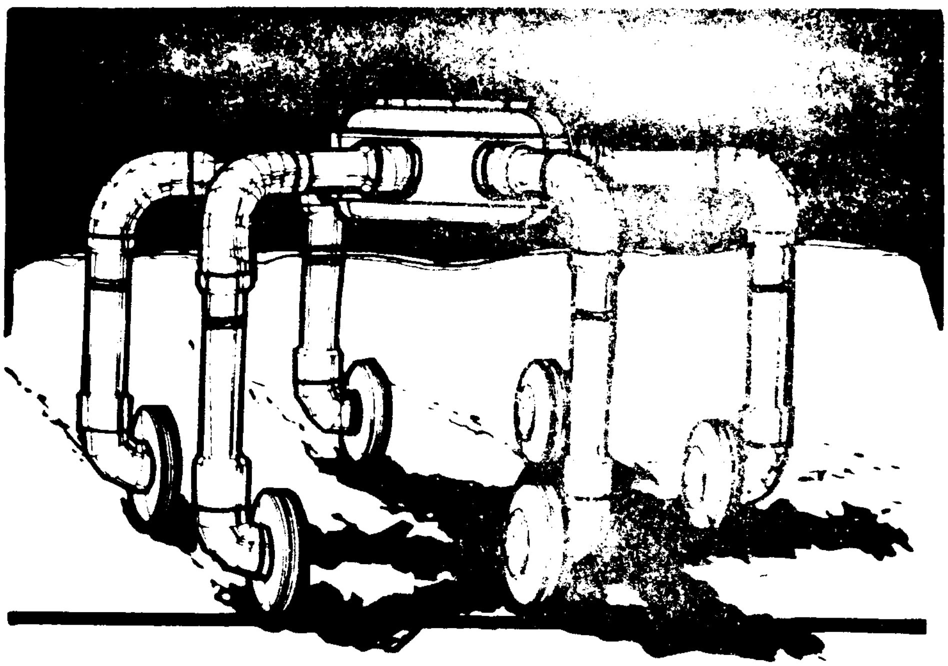

Figure 10. Six-strut machine in rolling mobility mode.

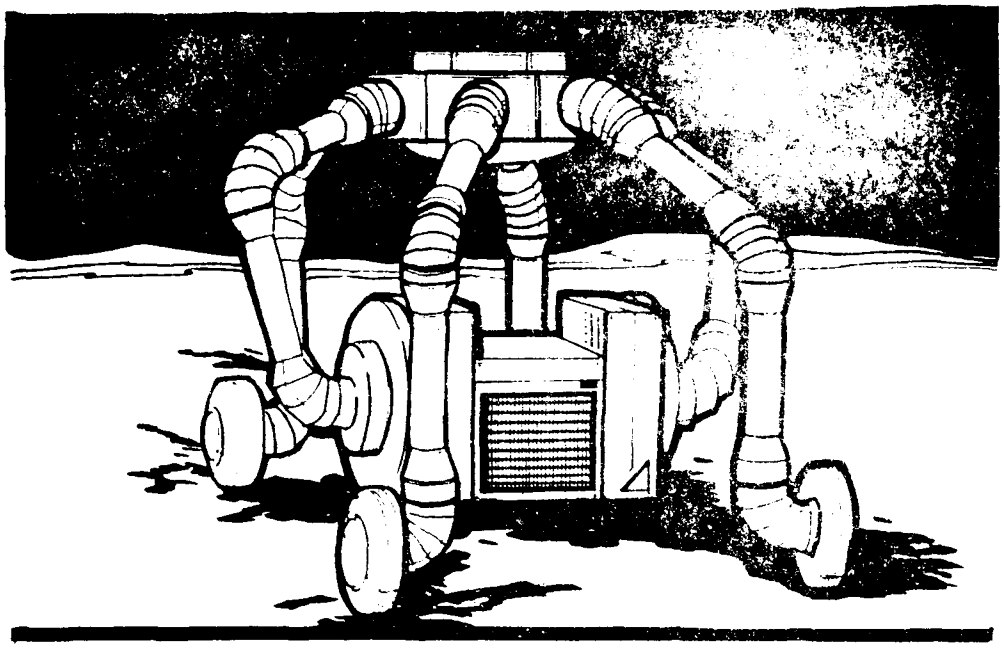

Figure 11. Cargo transport and handling struts.

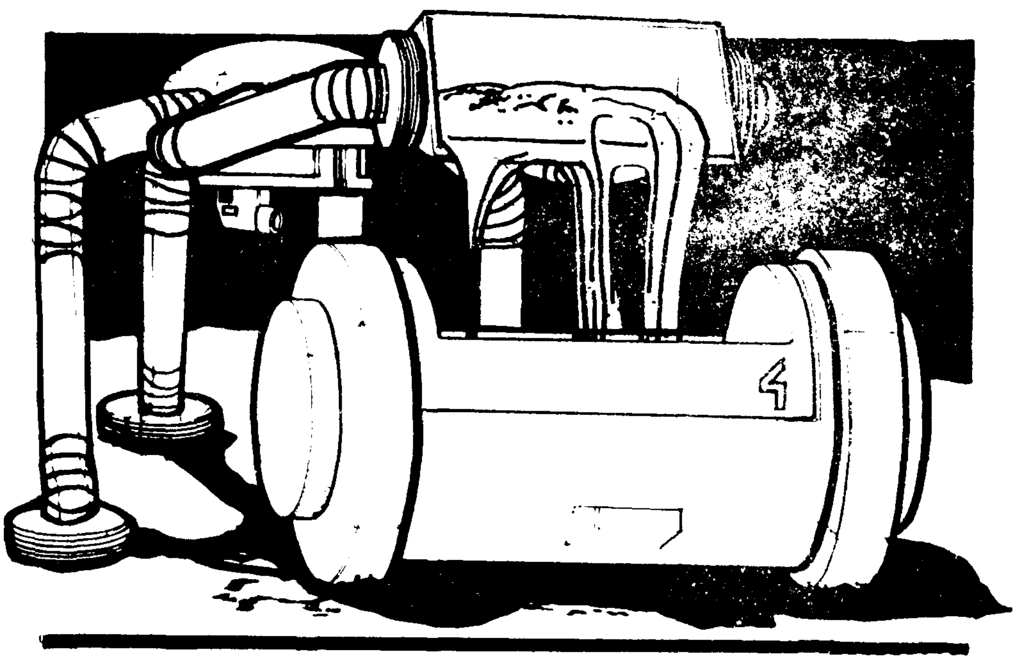

Figure 12. Manipulating a loader bucket to scoop and dump bulk material.

Various power cables, communication cables, and fluid lines will be needed to connect facilities to one another. Whether these utilities are to be supported on towers above the surface, placed on the surface, or covered in trenches, they must be deployed along a route from place to place. The method used here is to grasp a compatible spool of the cable and unreel it as both position over the trench and cable tension are maintained. The position of the cable is controlled by the struts as they cooperate to move the spool laterally. The cable tension is maintained by the wheel motors as the vehicle proceeds along the intended path.

Some operations, such as launch and landing, may require that cables be deployed temporarily, then retrieved. This retrieval process could be accomplished in a manner similar to the deployment task described above. Having the cable already connected to the spool will make retrieval much easier.

The spool can be manipulated by the two center struts, as shown in Figure 13, or the two forward or two rear struts if deemed more effective. The three-strut machines would require an implement mounted to the underside of the body. This implement would provide for grasping and rotating the spool. The other required motions would be available as body motions.

Cargo Bin (C)

The cargo bin is a simple open box-like implement. It will, for most tasks, be placed on the surface, filled with the intended cargo, attached to the work platform, and transported to the desired site. At this point, the bin will again be placed on the surface and unloaded. Its functions are analogous to the familiar terrestrial pickup truck body.

Casters (E)

The casters and their applications are described in more detail in other literature.[21] Some of these applications are in conjunction with the mobile work platforms described in earlier sections of this report. They are also used as independent vehicles for transporting bulk material as shown in Figure 14. They may be hitched together to form a train as shown in Figure 15. Figure 16 illustrates the means of dumping loose bulk material by taking advantage of the system's inertia.

Crane Assembly (F)

A top-mounted implement in the form of a boom crane is illustrated in Figure 17. The base of the crane is attached to the interface at three points and includes the turntable bearing. Full 360 degree rotation is thus available for boom rotation. The power source, boom lift actuator, and slewing actuator are located on the rotating element of the turntable. The winch is located at the tip of the boom to eliminate the compressive reaction load that the boom would be subjected to if the winch were located at the base. Eliminating this load reduces the structural requirements and thus the mass of the boom. Also note that the winch is mounted such that the line passes directly to the load without the use of a sheave or pulley. The position error that results as the line plays out or winds up can be compensated for by the boom movement. The legs of the mobile equipment platform are repositioned as necessary to serve as outriggers for stability of the machinery.

<u>Hoist Line</u>. The line material and cross section are not yet determined. Rational candidates include a stainless steel band (thin, wide), a woven glass rope, and a dry-film lubricated stainless steel wire rope. The stainless steel band is the strongly favored candidate. It is expected to be the most tolerant to dust

[21] James W. Brazell.

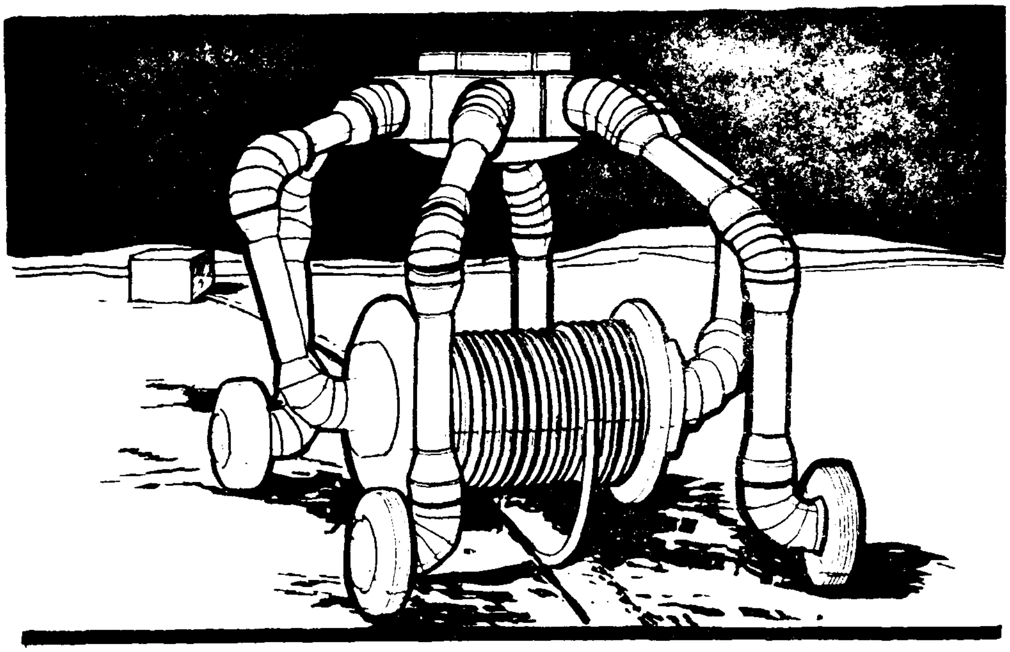

Figure 13. Cable deployment.

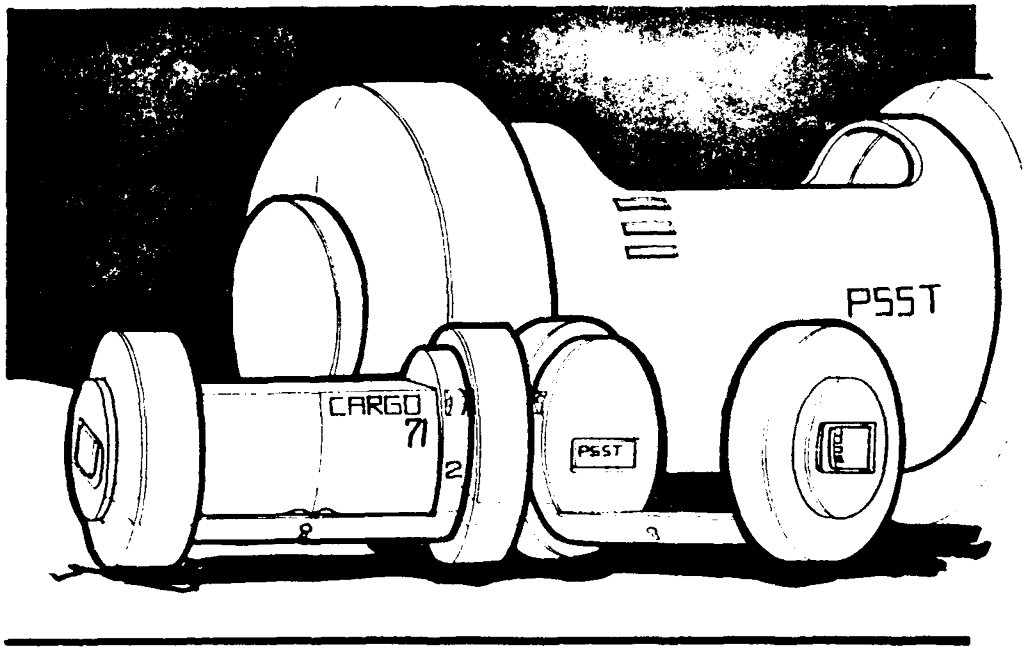

Figure 14. Casters as independent vehicles for transporting bulk material and cargo.

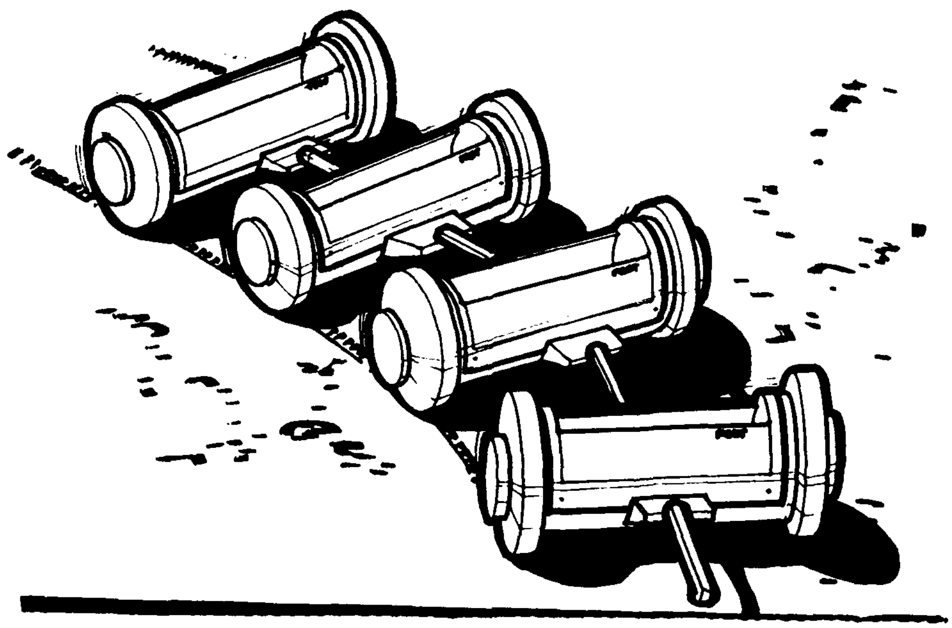

Figure 15. Casters as modules of a train.

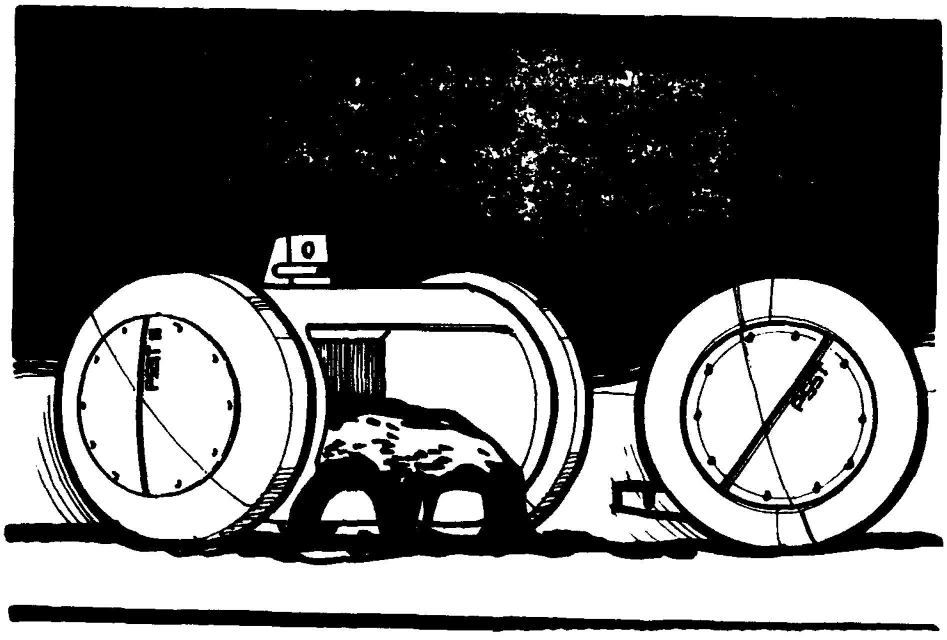

Figure 16. Dumping of loose bulk material.

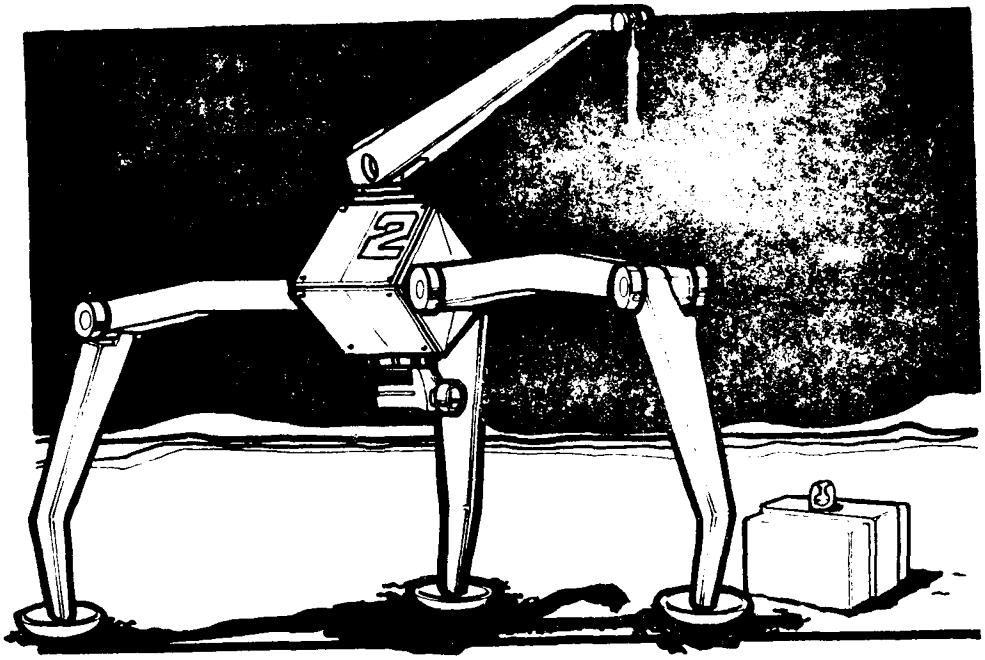

Figure 17. Crane assembly.

and is predictable in its windup form. The onset of failure can be more easily assessed by inspecting for elastic and plastic elongation. The band also has the advantage of acting as an oriented torsion spring to orient a load.

Crane-Cargo Interface. The common hook used on a terrestrial crane to engage the cargo, sling, or spreader beam, is not well suited to remote control of the engaging and disengaging actions. Engaging a ring on a cargo unit requires a given radial orientation of the hook relative to the ring before the hook is moved laterally into the ring and then upward to complete the connection. Without the assistance of a helper at the hook, or a rotating control actuator, achieving a connection would be frustrating at best. Assuming such a connection is made and the cargo is moved to a new location, the uncoupling of the hook can be even more difficult. If wire rope is used, it imparts a tendency of the hook to twist relative to the ring.

The proposed interface obviates the difficulties associated with radial orientation by having a form that is symmetrical about the cable centerline. This spherical form engages a compatible form on the cargo by first a radial motion, then upward motion. Once engaged, the cargo can tilt relative to the cable up to an included conical angle of about 30 degrees if needed. Following the placement of the cargo, the cable is let slack and moved to the side for the sphere to exit the cargo interface form. This form generally follows a lamp pull chain joint[22] and is illustrated in Figure 18.

[22] National Aerospace Standard (NAS) 1201, *Chain-Bead, Components, and Assembly*, (1983).

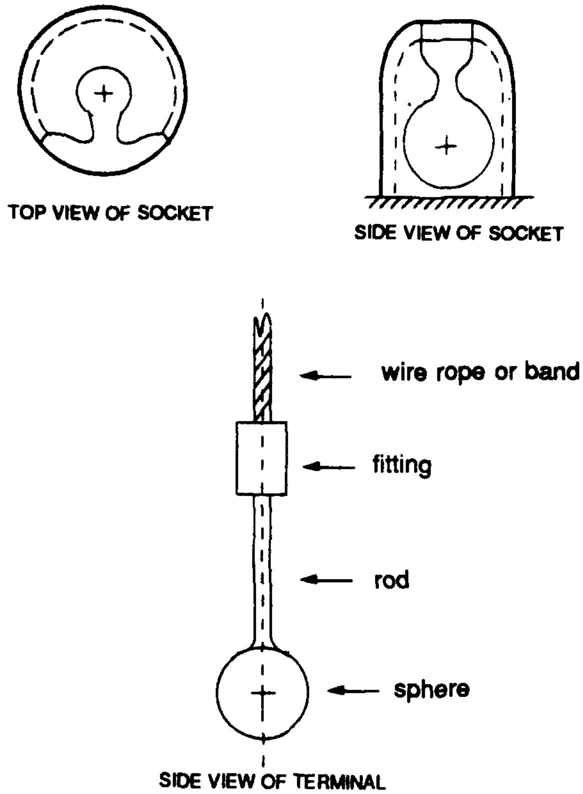

Figure 18. Line-to-load interface.

The line-to-load interface replaces the conventional hook and ring arrangement that is commonly used to handle cargo. The hook and ring would be difficult at best to connect and disconnect robotically using only the crane's degrees of freedom. The proposed terminal arrangement consists of a sphere attached to a rigid rod or tube which in turn connects to the end of the line (Figure 17). The socket is attached to the cargo to be handled. It has an opening in the side for the sphere and lower end of the rod. As the sphere enters this opening and is raised by the crane, engagement takes place. Proper engagement is maintained through a total of 60 degrees, the included conical angle between the rod and cargo, so long as the line remains in tension. This interface technology was evolved from the bead chain interface. To disengage the interface, the line and rod are trailed slack, away from the opening. The sphere will follow to disengage the interface. Line twist that results from load handling will be eliminated as the line goes slack. The geometry of the sphere and rod allow engagement/disengagement regardless of line position.

Reverse ClamShell (G)

A mechanical arm equipped with a clamshell end effector will be useful in general excavation work, especially trench digging and small boulder removal. This end effector is comprised, generally, of a pair of backhoe-like buckets mounted back-to-back. The buckets may be reversed or arranged in the conventional face-to-face configuration. Figure 19 illustrates the general arrangement of this implement, showing the three hinged joints in the mechanical arm and the rotary joint that connects the arm to the body of the mobile work platform.

The primary advantage of this arm/end effector configuration, in comparison to a terrestrial backhoe, is that the major forces can be confined to the end effector. This avoids the dependence on the tractive device for horizontal force. Also, the structure along the length of the arm and through the vehicle frame

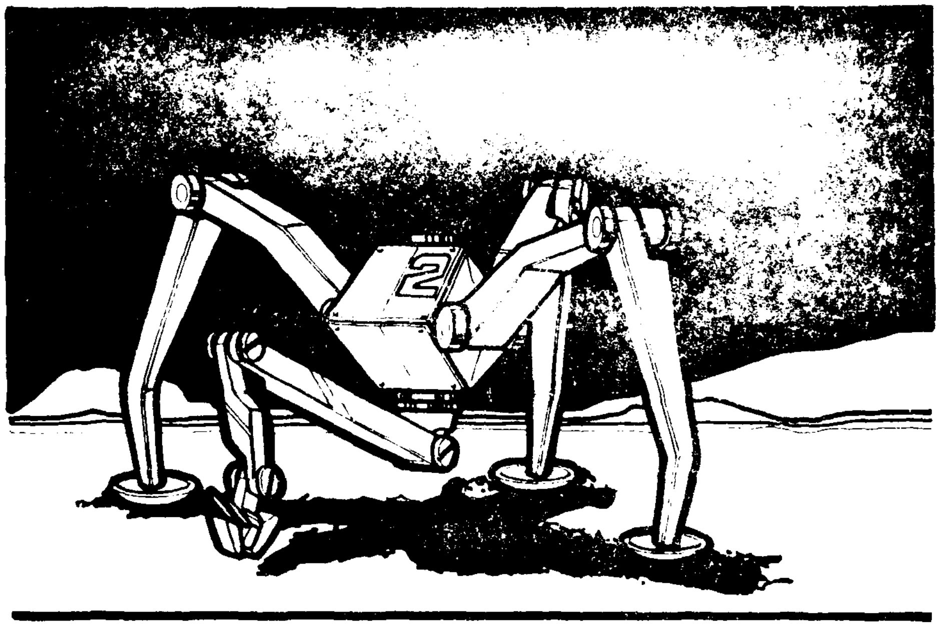

Figure 19. Reverse clamshell implement on the robotic arm.

to the traction surface need not be designed to withstand the large digging forces. For a given magnitude of digging force, this approach appears to yield the minimum of structural mass.

The end effector has one actuator, with coordinating linkage, to rotate the two buckets relative to the arm and a second actuator to provide relative transitional movement between the buckets. With the buckets in the reversed position, the kinematics is such that the end effector is self feeding into the regolith as the bucket tips move away from one another. If, in attempting to start this action, the downward force from the mobile work platform is insufficient, impact can be used to break loose a small quantity of compacted regolith. This is accomplished by positioning the buckets together and accelerating them generally downward with the arm. The loosened material can then be scooped by the buckets for piling near the hole or trench, or loading into a hopper or other container. Loosened material can also be manipulated with one of the buckets by rotating the second bucket out of the work path. Small boulders can be handled by the clamshell implement, provided the boulder size is within the grip capacity of approximately 1.0 meter. The inherent dexterity of the mobile work platform extends the work envelope of the mechanical arm by tilting, raising, or lowering the body. This feature is especially useful in digging deep holes and trenches as well as dumping into elevated hoppers or containers.

Each bucket has a level-struck capacity of 0.1 m^3 and the pair can close on as much as 0.2 m^3 of loose material. The lack of soil cohesion is of concern in that the clamshell might leak a significant quantity of small particles as a load is being handled.

Drill Implement (H)

One of the important attributes of the mobile work platform is its ability to function in concert with an implement at a worksite. This tends to simplify the implement-machine system by using the mobility

actuators to manipulate the implement. In the case of the drill implement, the platform provides the generally vertical straight-line motion along the drill axis as well as tilt angle and lateral offset motions.

The drill implement is attached (by the manipulating arm/end-effector) to the underside of the machine body at the lower implement interface and is comprised of a motor and spindle to rotate the drill tools and a reciprocating actuator to power a cutting removal device. Ancillary equipment associated with the drill includes a rod changer, a rod rack, a set (string) of rods, and a deployable footplate. The footplate supports the rod string as it is tripped into and out of the hole. Drill rods and down-hole tooling elements are handled by the rod changer which is a pick-and-place manipulator.

The down-hole tooling includes the basic bit and an inertial cutting removal mechanism. Hole size is expected to be approximately 100 mm in diameter and up to 50 m deep. Using the rock coring tool, a 30 mm diameter rock core can be retrieved. Penetration rate will be comparatively slow in the interest of avoiding excessive temperatures at the bit. No fluids are used by the proposed drill.

Regolith Bagger (I)

The regolith bagger is essentially a specially shaped hopper held a meter or two above the surface that uses the clamshell end effector and robotic arm to fill it. The loose soil is thus guided down a discharge chute and gravity-fed into small self-closing bags or into large saddle bags that are in place on a habitat or other structure requiring shielding.

Robotic Arm (J)

The robotic arm can be mounted to the upper or lower implement interfaces. For the LEVPU machine, several alternate positions on the body would be required to develop the necessary work envelopes. It is used for those small force tasks that require more precise motions and positioning than would be reasonable to expect from the mobile work platform.

Grader Blade (K)

Adding an implement to the lower interface enables the machine/implement set to perform various tasks. Referring to Figure 4, a grader blade has been added to shape and level the loose regolith. The blade is rigidly mounted to the body and is positioned by adjusting the various leg joints and wheel orientations. Vertical motion establishes depth-of-cut or raises the blade clear of the surface. This motion, as well as pitch and roll, results from appropriate adjustment of the hip and knee (or telescoping) joints. Blade yaw angle relative to the direction of travel is controlled by the orientation of the wheels. This capability depends entirely on the locomotion actuators.

In comparison to conventional terrestrial graders, it has all of the same degrees of freedom; however, some are adjustable over a smaller range while others may be adjusted over a larger range. Blade pitch and roll angles are more limited, while yaw, depth of cut, and travel direction are less limited.

The grader blade appears well suited to shaping and leveling loose or very loose soil, but is not suitable for working compacted material, especially that containing embedded rock of significant size. Several particularly arduous problems are associated with the latter case. A downward force is needed to cause penetration of the blade before soil working can begin. This downward force must be derived from the gravity force associated with the lunar weight of the machine. This gravity force must be shared with the traction device (wheels in this case) that also depend on a normal force. An embedded rock that the machine is incapable of moving may be encountered by the grader blade. This encounter will likely bring the entire vehicle to an abrupt stop or the blade will skip over the top of the rock. Either way, the load is transferred from the soil engaging blade through the machine's structure to the traction device.

Regolith is highly-compacted, dense material containing very angular and interlocking soil particles. Proposed lunar excavation methods based on terrestrial methods require the insertion of an implement or cutting edge into the soil. This act of insertion displaces particles within the densified soil matrix, induces shearing and crushing of many particles, and, for high productivity, requires large forces that must be generated by massive, powerful machines. The Boles Lunar Excavator concept[23] represents a departure from previously proposed methods in that it avoids the fundamental problem of hard soil penetration by using a brush-type mechanism.

Instead of removing soil in large portions, it removes soil at the particulate level, a few particles at a time. It does this at a very rapid rate; therefore, the expected production is very high. The device is envisioned to be composed of various brush-like devices that are rotated at a relatively high velocity. The bristles remove those particles that are exposed at the surface of the highly-compacted regolith and pass over particles and rocks that are embedded. As the surface particles are removed, embedded particles are exposed to be removed by subsequent bristles. As the fines are removed from around embedded rocks they would disengage and segregate out of the regolith material.

Figures 20 and 21 illustrate grading and trenching tasks, respectively. In both cases, one wheel holds and powers the shaft while the other holds the guard in place. The downward and horizontal forces required to operate such a device have been shown, in some preliminary tests at Pacer Works, Ltd., to be about an order of magnitude less than those of comparable soil penetrating tools. This enables very lightweight machines to be productive in excavating the compacted regolith.

Supervisory Module (L)

Control of the machine is likely to involve some form of vision system for the remote operator. A machine-mounted video camera such as shown in Figure 22 is very limited in the location and orientation of its field of observation. Further, the soil engaging implements are certain to add considerably to the quantity of dust in the environment near the machine. This dust is expected to be detrimental to the performance of the lenses of a machine-mounted video camera.

The use of an independent supervisory module (perhaps a separate rover that could be maneuvered and set up at advantageous viewing points) with stereo-vision devices overcomes these two difficulties and provides still other benefits. It is intended to perform many of the functions associated with a worksite foreman. The module (nicknamed FOBOT) would be transported to and set up at the most favorable position at a worksite in preparation for the tasks to be undertaken. The module's instruments could include radar for range finding and imaging video cameras for direct vision, plus communication and navigation systems. Other systems could include contact and remote temperature sensing, vibration analysis, and other diagnostic capabilities.

The module would serve as a central controller for the several machines that might be used simultaneously at a worksite. Risk of accidental contact between machines and static elements should be minimized by having all machines controlled from one point. All of the machines from Earth or any other location would use the module as a relay element. The communication, navigation, and control systems on board each machine can thus be much simpler. Orientation of thermal radiators, solar collectors, and antennae could be better for the portable module than with a mobile machine. The electronics within the module would not be subjected to the shock and vibration experienced by that mounted on the work machines.

The productivity of the module would be defined by the number of machines under its control and the complexity of the tasks being performed simultaneously.

[23] Walter Boles Personal Communication, Department of Civil Engineering, Texas A & M University, College Station, Texas, July 1989.

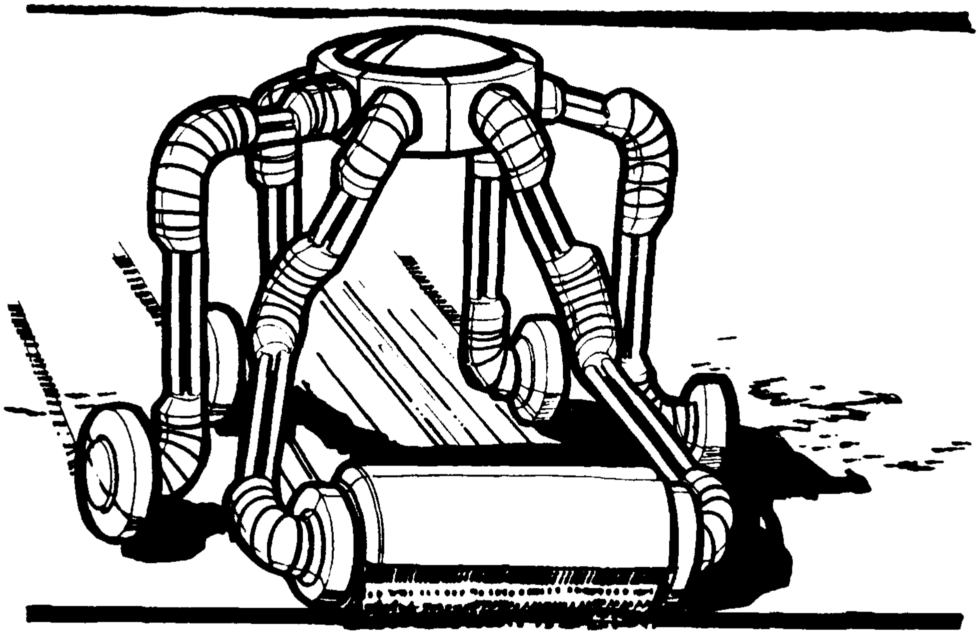

Figure 20. Grading with a Boles Lunar Excavator.

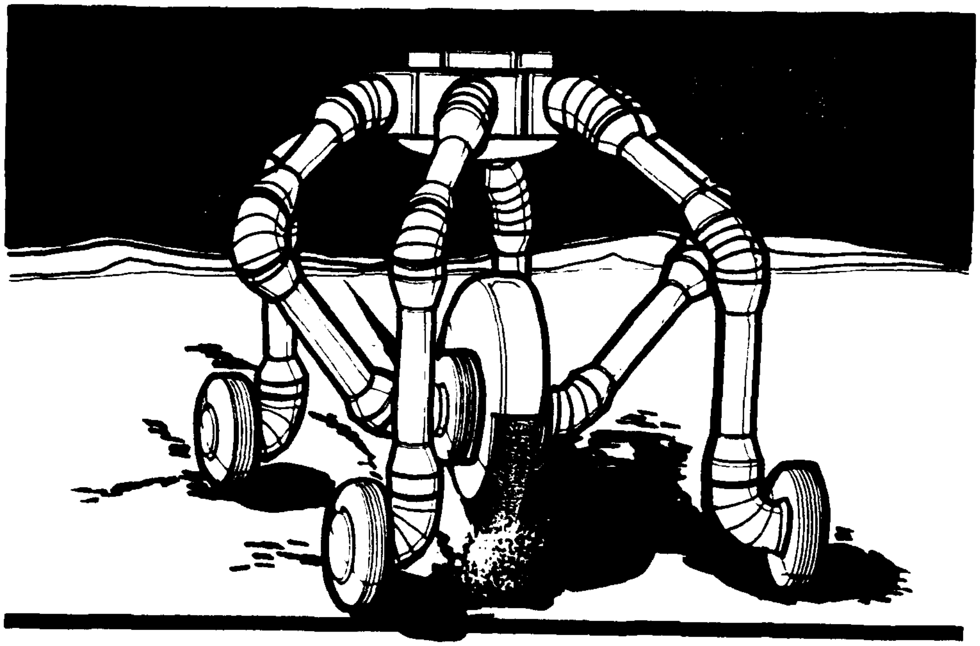

Figure 21. Trenching with a Boles Lunar Excavator.

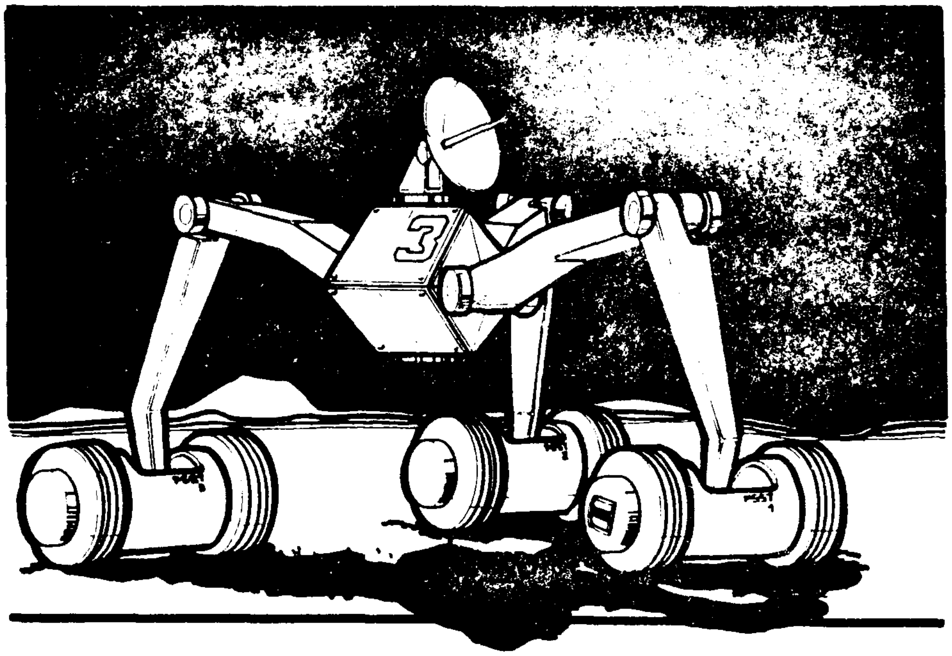

Figure 22. Supervisory module - FOBOT.

4 CONCLUSIONS AND RECOMMENDATIONS

The conceptual designs developed in this research appear to be capable of performing the required tasks on the lunar surface and meet the mass constraints prescribed. The designs are based on 1990 technology with the exception of the control systems. Material choices have been significantly influenced by repairability considerations. Additional launch mass reduction may be achieved as experience is gained with using composites in the lunar environment.

The conceptual models are principally mobile work platforms that can be moved about on wheels or walking struts. Various end effectors that perform specific work tasks (e.g., scooping or drilling) are attached to the platforms at a standard interface.

1. Refine the definitions of those tasks that the machines and equipment are to perform and the associated productivity rates required for mission success.

2. Select the site or sites for the outpost or base and the area(s) likely to be traversed and characterize these, especially with regard to the soil/machine interactions.

3. Support the immediate development of suitable control systems, both hardware and software, to direct the actions of the machines as they perform the required tasks. Design the systems to accommodate future developments.

4. Identify those enabling and high leverage technologies (including use of superhard materials) that might influence the general tract of the designs.

5. Conduct the required research, study, development, and testing to certify worthiness of the machines.

6. Start the research early enough to allow adequate testing to verify those technologies and methodologies used in the final machines.

7. Use a plurality of identical mobile work platforms with a set of interchangeable implements to accomplish the tasks identified. More research on both mobile work platforms and implements must be conducted with verification test and evaluation studies conducted in test facilities that simulate, as closely as possible, the lunar environment.

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